Textile reinforced mortar versus FRP for confined concrete: Behaviour at elevated temperatures

TEXTILE REINFORCED MORTAR VERSUS FRP FOR CONFINED CONCRETE: BEHAVIOUR AT ELEVATED TEMPERATURES

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ABSTRACT

Despite the clear advantages of confinement of concrete structural elements with fibre-reinforced polymers (FRPs) for strength and deformability enhancement, concerns as to their performance at elevated temperature, or in fire, remain. The results of a series of elevated temperature experiments on FRP and textile reinforced mortar (TRM) strengthening systems for confinement of circular concrete columns are presented. The behaviour and effectiveness of the respective confining systems is studied up to temperatures of 400°C. A total of 24 concrete cylinders were wrapped in the hoop direction with different amounts of FRP or TRM, heated to steady-state temperatures between 20 and 400°C, and loaded to failure in concentric axial compression under a steady-state thermal regime. The results indicate that the effectiveness of the FRP confining system bonded with epoxy decreased considerably, but did not vanish, with increasing temperatures, in particular within the region of the glass transition temperature of the epoxy resin/adhesive. Conversely, the TRM confining system, bonded with inorganic mortar rather than epoxy, demonstrated superior performance at 400°C as compared against tests performed at ambient temperature. Additional research is needed to better understand the reasons for this.

KEYWORDS

FRP, textile reinforced mortar, TRM, strengthening, high temperature, fire, confinement.

INTRODUCTION

A popular application of FRP is strengthening concrete columns by confinement with FRP in the hoop direction (Bisby *et al.* 2011). However, the performance of FRP systems at elevated temperatures is potentially problematic since much of their strength, stiffness, and bond properties are lost at temperatures that are rapidly exceeded in building fires (Chowdhury *et al.* 2011). Carbon fibres used in FRP systems are capable of resisting temperatures of more than 800°C; however, epoxies used to bond the fibres and adhere FRP systems to concrete lose a considerable proportion of their mechanical properties at temperatures as low as 60°C-82°C (ACI 2008). These reductions in mechanical properties can be expected in the region of the epoxy's glass transition temperature (T_g) as it changes from hard and brittle to soft and plastic. Testing has been carried out previously to investigate the performance of FRP confining systems for concrete columns during standard fire exposures (e.g. Chowdhury *et al.* 2007) and during both transient and steady-state heating to elevated temperatures (Rickard *et al.* 2013). This testing has shown that considerable (approximately 50%) loss of effectiveness of the FRP strengthening system occurs at temperatures as low as 15°C below the T_g of the epoxy adhesive, which is thought to be due to reductions in the tensile strength of the FRP wraps at these temperatures. To alleviate the reduced effectiveness of FRP systems at high temperatures, a novel textile-reinforced mortar (TRM) has been proposed for strengthening of reinforced concrete (RC) columns [Bournas *et al.* 2007]. In an effort to develop strengthening systems with enhanced performance at elevated temperatures, this paper presents initial research aimed at investigating the performance and effectiveness of both FRP and TRM confining materials of concrete *at elevated temperatures*, such as would be experienced during a fire, when the confining system is *active under sustained load*; this was done by testing concrete cylinders with different amounts of FRP or TRM confinement at various temperatures. The main objective was to develop an initial understanding of the confining mechanisms at elevated temperature and to suggest defensible limiting temperatures for FRP and TRM strengthening systems in fire.

EXPERIMENTAL PROGRAM

Thirty tests were performed on normal strength concrete cylinders that were loaded at both ambient and elevated temperatures. All tests were performed under a steady state thermal regime. Since this is the first ever study of its kind; a goal of the study was to identify aspects for further investigation. Details of the experimental program are given in Table 1. All tests were on 100mm diameter, 200mm tall concrete cylinders; this was chosen as it allowed test specimens to fit within a bespoke environmental chamber fitted within a 600kN materials testing frame; it is noteworthy that a size effect may be relevant to the performance of both FRP and TRM wrapped cylinders, and additional research is needed on this topic. Parameters varied within the testing program included:

- *Type and amount of confinement:* Six cylinders were tested without confinement to determine the unconfined concrete properties and to determine the reductions in concrete properties caused by heating to the maximum exposure temperature used (400°C). Twelve cylinders were wrapped with FRP (six with a single layer and six with three continuous layers). The fibres used were carbon textile reinforcement with an open weave and a weight of 220g/m^2. The fibres' manufacturer datasheets (Bentonex RC225-TH12) gave a tensile strength and modulus of elasticity of the carbon fibres was 4800MPa and 225GPa, respectively, with a nominal thickness of 0.062mm (Bentonex 2016) (trade names given only for factual accuracy). The fibres were saturated and bonded using Sikadur 330 epoxy adhesive system (Sika 2016). The TRM system also used Bentonex RC225-TH12 carbon fibre textile reinforcement. This was bonded with a cementitious mortar based on an inorganic dry binder consisting of cement and polymers at a ratio of 8:1 by weight, ISOMAT (2016). The water-binder ratio in the mortar was 0.23:1 by weight, resulting in plastic consistency and good workability. The hoop overlap length was chosen as 100 mm.
- *Thermal Exposure:* Temperatures were chosen in the range of the glass transition temperature (T_g, as determined from dynamic mechanical analysis) and the decomposition temperature (T_d, as determined from thermogravimetric analysis) of the epoxy adhesive/saturant. The epoxy resin used in the current study has a T_g of 58°C based on tan delta peak from DMA testing. Samples were heated without any applied load at a heating rate of 10°C/min until the target temperature was reached, and all samples were then held at the target testing temperature for 60 minutes before testing (to assure a uniform sample temperature).

Table 1 Details of the Experimental Program

No.	Wrapping	Matrix/ Adhesive	Exposure Temp. (°C)	Comments
1	--	--	20	Control tests on unconfined concrete at ambient (with repeat test)
2				
3			100	Control tests on unconfined concrete at elevated temperature
4			150	
5			200	
6			400	
7	Single layer of FRP	Epoxy	20	FRP confined concrete at ambient
8			80	Temperatures in the range of T_g*
9			100	
10			150	Temperatures well above T_g*
11			200	
12			400	Temperature in the range of T_d**
13	Single layer of TRM	Mortar	20	TRM confined concrete at ambient
14			100	Single layer of TRM at various temperatures
15			150	
16			200	
17			400	
18				Repeat test at 400^{o}C
19	Three layers of FRP	Epoxy	20	FRP confined concrete at ambient
20				Repeat test at ambient
21			100	Temperature in the range of T_g*
22			150	Temperatures well above T_g*
23			200	
24			400	Temperature in the range of T_d**
25	Three layers of TRM	Mortar	20	TRM confined concrete at ambient
26			100	Three layers of TRM at various temperatures
27			150	
28			200	
29			400	
30				Repeat test at 400^{o}C

* T_g – epoxy glass transition temperature; **T_d – epoxy decomposition temperature

All samples were tested in an Instron 600LX testing frame with an integrated environmental chamber at a loading rate of 1mm/min (crosshead displacement) until failure. Axial and hoop strains were measured using image correlation analysis via digital images captured every 5 seconds during testing with post-testing analysis performed in GeoPIV software (White *et al*. 2003). Full details of the image analysis technique are avoided here but have been presented for similar testing by Rickard *et al.* (2013). Temperatures were monitored during testing by a single thermocouple for air temperature (placed next to the sample) and a single thermocouple mounted on the surface of the sample at mid-height. Testing occurred six months after casting the concrete.

EXPERIMENTAL RESULTS

Summary plots showing the results of all tests listed in Table 1 are given in Figure 1, and numerical summaries of the tests are given in Table 2.

Table 2 Summary of Test Results

No.	Wrapping	Target Exposure Temp. (°C)	Temp. at Failure (°C)		Peak Load (kN)	Peak Stress (MPa)	Failure Mode*
			Air	Surface			
1	--	20	20	20	132.0	16.8	--
2			20	20	121.2	15.4	--
3		100	99	96	107.2	13.6	--
4		150	150	139	111.4	14.2	--
5		200	200	189	134.3	17.1	--
6		400	400	362	127.3	16.2	--
7	Single layer of FRP	20	20	20	255.1	32.5	Rupture
8		80	76	74	220.2	28.0	Rupture
9		100	94	93	161.1	20.5	Mixed
10		150	148	145	142.6	18.2	Mixed
11		200	196	186	179.6	22.9	Adhesive
12		400	394	370	165.6	21.1	Adhesive
13	Single layer of TRM	20	20	20	243.1	31.0	Rupture
14		100	94	93	182.3	23.2	Rupture
15		150	146	143	192.8	24.5	Mixed
16		200	195	186	201.4	25.6	Rupture
17		400	377	369	266.4	33.9	Mixed
18			386	375	227.5	29.0	Rupture
19	Three layers of FRP	20	20	20	491.6	62.6	Rupture
20			20	20	494.0	62.9	Rupture
21		100	93	91	367.4	46.8	Rupture
22		150	147	139	328.9	41.9	Mixed
23		200	195	188	328.1	41.8	Adhesive
24		400	384	371	302.2	38.5	Adhesive
25	Three layers of TRM	20	20	20	330.5	42.1	Rupture
26		100	93	89	303.1	38.6	Mixed
27		150	146	141	290.1	36.9	Rupture
28		200	194	186	317.8	40.5	Rupture
29		400	396	371	353.7	45.0	Mixed
30			383	362	353.1	45.0	Mixed

* "Rupture" refers to FRP failure in hoop tension, "adhesive" refers to loss of confinement by debonding, "Mixed" refers to failure which displayed a combination of rupture/adhesive failure

Unconfined Concrete Cylinders

Six unwrapped (plain) concrete cylinders were tested. Two were tested to define ambient strength, and the remaining four were tested at selected elevated temperatures (100°C, 150°C, 200°C and 400°C) in order to assess the effects of elevated temperature on the strength and stiffness of the unconfined concrete; such that any strength reductions observed for the FRP and TRM confined specimens could be attributed (or not) to reductions in the effectiveness of the confining mechanism. The average ambient unwrapped concrete strength was 16.1 MPa. The concrete strength was reduced slightly, by 15% and 12% at 100°C and 150°C, respectively, before recovering to a strength 5% above that at ambient at 200°C. At 400°C there was no obvious reduction in compressive strength. Whilst its difficult to draw definitive conclusions regarding the effects of elevated temperature exposure on the plain concrete cylinders due to the small number of specimens tested, it is noteworthy both that these test data contradict the widely accepted concrete strength reductions with temperature suggested in the Structural Eurocodes (CEN, 2004) – which indicates an expected compressive strength reduction of between 15 and 20% at 400°C, depending on the aggregate mineralogy – and that similar strength trends seem to underlie the responses of the FRP and TRM confined specimens (discussed below). The lack of reduction in compressive strength of the concrete at 400°C suggests that additional research is warranted in this area.

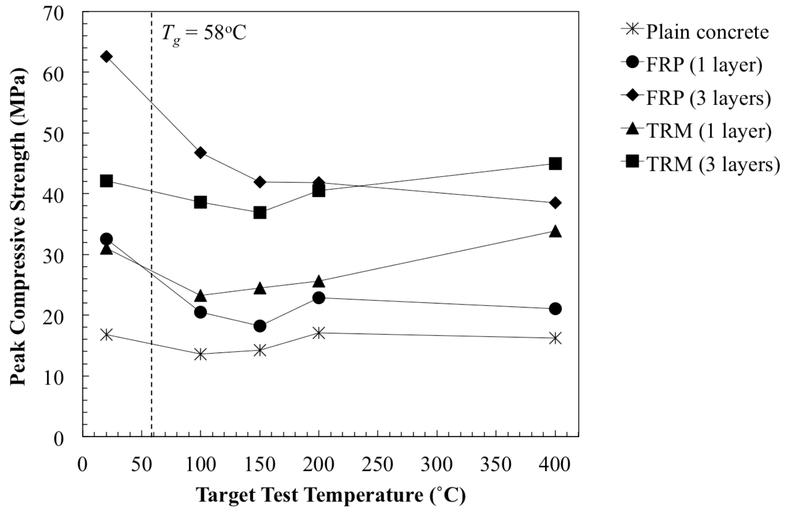


Figure 1 Ultimate Compressive Strength and Percentage Strengthening versus Temperature

Tests on FRP Confined Concrete

Figure 1 and Table 2 show a clear trend of reducing FRP confined concrete strength with increased steady state exposure temperature; although with such a small number of samples it is difficult to clearly distinguish if this is attributed to concrete thermal damage effects and/or loss of FRP confinement effects. Whilst the results for FRP confined cylinders are similar to those previously reported by Rickard *et al.* (2013), additional testing with a larger number of cylinders will be required to have greater statistical confidence in the results obtained.

It is clear that exposure temperatures above T_g cause considerable reductions in the strength of FRP confined concrete cylinders. It is also clear, however, as previously reported by Rickard *et al.* (2013), that the FRP wrap provided considerable additional strength at all temperatures tested, particularly for the case with three continuous layers of carbon fibre reinforcement. For the case of three layers of FRP, the confinement continued to enhance the failure strength at temperatures well above T_g. For example, strength was enhanced by more than 200% at 400°C. The confinement provided by the single layer of FRP is much less; this is likely the result of frictional bond strength for the three layer wrapping, which is able to provide confinement even once the adhesive has lost the majority of its mechanical properties.

Tests on TRM Confined Concrete

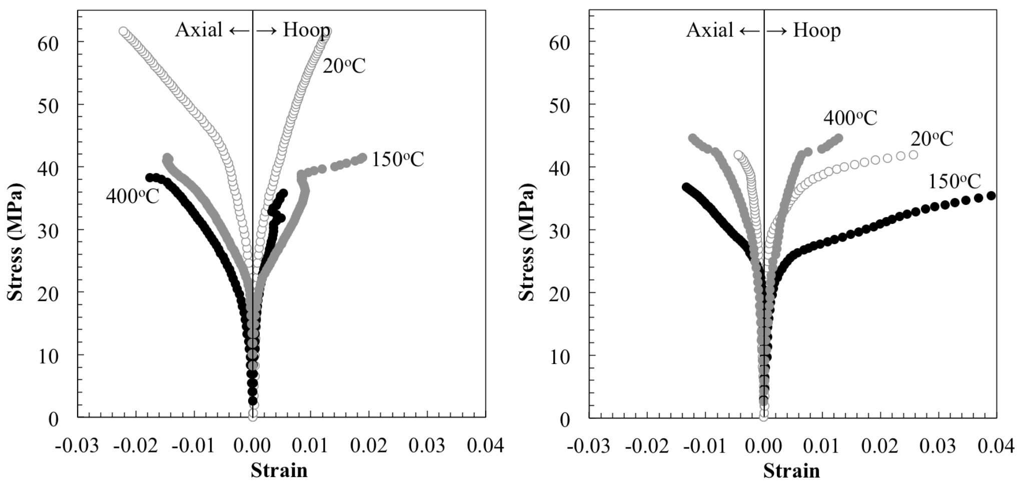
For the TRM confined concrete cylinders, Figure 1 and Table 2 show that the TRM system was marginally less effective than the FRP system for a single layer at ambient conditions, and that it's performance was similarly affected by exposure to a temperature of 100°C, losing 23% of its strength at this temperature. This is likely due to a combination of reductions in the strength of the concrete itself at this temperature (discussed previously) combined with reductions in the effectiveness of the confinement (for reasons which remain unknown). However, at temperatures above 100°C the TRM system recovered its strength more rapidly than either the plain or FRP confined specimens, and at 400°C the single layer TRM confined sample actually tested stronger than the sample tested at ambient.

Similar observations can be made regarding the performance of the three layer TRM confining system. In this case the strengthening provided by the TRM system was considerably less, by 33%, than the three layer FRP system, probably because of differences in the observed failure mode; tensile pull-out of the fibres from the cementitious matrix followed by partial fibre fracture in the case of the TRM, compared with tensile fibre fracture over the height of the cylinder in the case of the FRP. Figure of the TRM wrapped specimens was considerably less violent and absorbed more energy than for the FRP wrapped specimens, particularly at lower temperatures. This may present advantages, particularly in seismic strengthening applications. However, at elevated temperature the three layer TRM system displayed similar response as for the single layer TRM system, with mild reductions in strength at 100, 150, and 200°C (likely for the reasons discussed in the previous paragraph), but a small increase (by 7%) in strength at 400°C as compared with the strength at ambient.

Increases in the effectiveness of the TRM system at elevated temperature are striking, particularly for the case of the three layer TRM system, and may be due to thermal prestressing of the carbon fibres during heating, as has previously been suggested by Rickard *et al.* (2013) for multiple layer FRP confining systems at elevated temperature. Since carbon fibres generally have a negative coefficient of thermal expansion, whereas the concrete core has a positive coefficient of thermal expansion, thermal dilation of the concrete core during heating will develop tensile stresses in the carbon fibre mesh, and provided that bond is maintained (either by adhesion or by winding friction) the wrap will self-prestress, which can be expected the enhance both the strength and stiffness of the TRM confined cylinders. This hypothesis warrants additional research, and may indicate that unprotected TRM systems are capable of providing effective (i.e. active) confinement of concrete at temperatures up to and exceeding 400°C (something that epoxy-based FRP systems are unable to do).

Axial/Hoop Stress versus Strain Response

Typical stress-strain curves obtained during steady state testing using the image correlation analysis are given in Figure 4. For clarity only the ambient temperature, specimens confined with three layers, 150°C, and 400°C tests are shown. It was difficult to obtain consistent strain information during these tests due to thermal effects on the image correlation technique; the results should therefore be taken as only indicative of the response. It is noteworthy that both the strength and stiffness of the confined concrete appear to be significantly reduced at 150°C, whereas these appear to be recovered at 400°C. Again, this behaviour warrants further investigation, both for confinement research but also for structural fire engineer research on concrete structures. Further image correlation analysis results will be presented at the conference.



(a) (b)

Figure 2 Stress-Strain Curves for Cylinders with Three Layers of Strengthening: (a) FRP wraps, and (b) TRM wraps

PRELIMINARY CONCLUSIONS

The following preliminary conclusions can be drawn on the basis of the tests reported herein:

- Considerable loss of effectiveness of the FRP wrap system occurred at temperatures as exceeding the T_g of the epoxy adhesive used. This is thought to be due to reductions in the tensile, and more importantly bond, strength of the FRP wraps at these temperatures.
- The ultimate load capacity of FRP wrapped cylinders continued to decrease with increasing temperatures; however the FRP wrap continued to provide some confinement at all exposure temperatures, both for a single layer and for a triple layer, even at 400°C which is well above T_g. This is possibly attributed to bond retention resulting from winding friction, which appears to be (as expected), much more effective for three continuous layers of FRP than for a single layer.
- FRP rupture was the observed failure mode at temperatures below 100°C; above 100°C the failure mode was observed to transition to bond failure in the FRP overlapping zone.

- Minor loss of effectiveness of the TRM wrap system occurred at temperatures between 100 and 200°C. This is thought to be due to reductions in the compressive strength of the concrete at these temperatures (as corroborated by compression tests on unconfined concrete at these temperatures). However, both single and triple layer TRM wrap systems demonstrated enhanced strength at 400°C.
- It appears that differential thermal expansion between the carbon fibre reinforced wraps (contracting) and the concrete column (expanding) caused a slight prestress of the FRP and TRM systems during heating.
- The number of FRP and TRM layers of wrapping (hence the effective overlap length used) had a significant impact on the confinement effectiveness at elevated temperature; however, additional testing is required to study the influence of wrapping with multiple continuous layers on the performance of FRP and TRM confined concrete at elevated temperature.

RECOMMENDATIONS

The following are recommendations for future work in this area:

- Further tests on unconfined concrete at elevated temperature are required to better understand the effects of heating on reduction in unconfined concrete compressive strength.
- Additional repeat tests, particularly on FRP and TRM confined concrete, are required to ensure statistical confidence in the results obtained and to corroborate the results and hypotheses presented herein.
- Other available FRP and TRM wrap systems and materials need to be studied to allow generalization of the observations made during the current study.
- Cylinders tested in this project were subjected to loads at elevated temperatures for relatively short periods of time. The potential effects of prolonged loading and heating, as might occur in warm service temperatures, require study since creep may cause failure at lower temperatures under long term loading.
- Additional tests should be conducted on FRP and TRM confined RC columns at full-scale.

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